

On the Magnetic Qualities of some Alloys not Containing Iron.

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The exhibition by one of us (Mr. R. A. Hadfield) at the British Association Meeting at Cambridge in 1904, of a sample of a magnetic alloy first prepared by Dr. Heusler, composed of copper, aluminium, and manganese, having aroused considerable interest, we felt that the quantitative measurement of the principal magnetic constants of such a material would be of very considerable interest. We, therefore, undertook at the earliest moment experiments with this object in view, and the following paper contains an account of the preliminary results obtained. For the purposes of exact magnetic measurements it was necessary to prepare the material in the form of homogeneous rings of regular form. This part of the work was undertaken at the Hadfield Steel Works, Sheffield, and in the early part of January, 1905, two such rings of alloys not containing iron were sent to the Pender Electric Laboratory of University College, London, for the magnetic tests.

These two rings were respectively numbered No. 1871 and No. 1888/7. Their chemical constitution was as follows:—The ring No. 1871 had the following composition: Manganese, 22·42 per cent.; copper, 60·49 per cent.; aluminium, 11·65 per cent. There is a certain amount of intermingled slag, probably 2 or 3 per cent., mostly consisting of MnO and SiO₂ and slight traces of other metals. Analysis showed that there was present also: Carbon, 1·5 per cent.; silicon, 0·37 per cent.; and iron, 0·21 per cent. Hence it may be said that nothing but a trace of iron occurs in this sample of alloy.

The other ring No. 1888/7 had an approximate composition: Manganese, 18 per cent.; copper, 68 per cent.; aluminium, 10 per cent.; lead, 4 per cent. These alloys unfortunately have poor mechanical properties and are brittle and cannot be forged. Rings were cast from the material and turned in the lathe to the desired form.

The rings having been carefully shaped, their dimensions were then measured. Both rings had approximately a mean diameter of 12·4 cms. and a square cross-section of approximately 1 cm. axial depth and 1 cm. radial breadth.

Each ring had four diametral lines, marked on it at angular intervals of 45°. As the ring No. 1871 was very slightly tapered, measurements were made on the front and back face and the means taken as follows:—

Outside Diameter of Ring No. 1871.

Along diameter.	At back in cms.	At front in cms.	Mean in cms.	} Mean outside diameter = 12·3765 cm.
1—5	12·390	12·360	12·375	
2—6	12·384	12·358	12·371	
3—7	12·392	12·368	12·380	
4—8	12·390	12·370	12·380	

The axial depth and radial breadth were then measured in the same eight positions:—

Position.	Breadth.		Depth.	Position.	Breadth.		Depth.
	Back.	Front.			Back.	Front.	
1	1·056	1·050	1·060	5	1·060	1·042	1·056
2	1·056	1·044	1·052	6	1·064	1·046	1·058
3	1·058	1·044	1·058	7	1·062	1·046	1·058
4	1·058	1·050	1·062	8	1·064	1·042	1·054

The resulting mean dimensions of the ring are, as follows:—

Ring No. 1871.

Mean outside diameter	12·3765 cm.	Mean depth.....	1·0572 cm.
Mean inside ".....	10·2713 "	Area of cross-section	1·1129 square cm.
Mean breadth	1·0526 "	Length of magnetic circuit or mean perimeter	35·576 cm.

The ring was then carefully wound over with primary and secondary electric circuits. These consisted of double silk-covered copper wire, well insulated with shellac varnish.

The ring was first given a coat of shellac varnish made up with absolute alcohol and after drying was wound over with four separate secondary circuits, placed in the four quadrants. These each consisted of one layer of silk-covered copper wire (No. 30 S.W.G.) and were numbered respectively 1, 2, 3, and 4. The turns were counted by more than one observer and after varnishing and drying the outside width and depth over, the winding was again measured so as to calculate the excess of the area included by the median line of each secondary wire turn, over and above the cross-sectional area of the ring of alloy itself. The results were as follows:—

Secondary coil.	Number of turns of wire in coil.	Mean outside depth, in cms., over winding.	Mean outside breadth, in cms., over winding.
1	208	1·154	1·1415
2	197	1·152	1·137
3	204	1·150	1·140
4	207	1·150	1·135

The secondary coils were then covered with a layer of silk tape and varnished, and after drying, the primary magnetising coil was wound on in three layers. This consisted of No. 18 double cotton-covered copper wire, the three layers having respectively 217, 206, and 197 turns. Between each layer a winding of varnished silk tape was interposed.

The ring so wound over uniformly with secondary and primary coils was mounted on a board with screw terminals at the ends of the various circuits. From the dimensions taken, the mean area included by the central line of one turn of the secondary circuit can be calculated, and it is 1·2097 sq. cms. Since the mean cross-sectional area of the ring is 1·1129 sq. cms., the difference between these two must be reckoned as an air space which is traversed by the magnetic flux due to the primary coil alone.

The magnetic measurements were made in the usual way with a ballistic galvanometer. A Paul movable coil ballistic galvanometer, having a periodic time of about four seconds, was employed. The secondary coil on the ring was joined in series with the galvanometer coil, with a resistance box and with a secondary standardising coil, which last was inserted in the interior of a long helix or primary standardising coil, in which a known magnetic field could be created by a measured current. The currents were measured by a potentiometer. The usual methods were adopted for determining the magnetisation curve and the hysteresis loops of a sample of magnetic material in the form of a ring. A known primary current was reversed through the primary coil on the ring and the throw of the ballistic galvanometer observed.

The meaning of the deflection was interpreted by breaking or reversing a measured current through the primary standardising coil. It is not necessary to enter into details of the arrangements, as they are familiar to everyone in the habit of using the ballistic galvanometer for magnetic measurements.

The cyclical magnetisation curves were, in all cases, taken by applying to the ring a known maximum magnetising force, and then dropping suddenly from this to a smaller value in the same direction, or to one in the opposite direction. In this manner the change in the flux, passing through the secondary coil in passing from a certain maximum flux to a lesser or oppositely

directed flux, was determined and the cyclical magnetisation curves set out as usual.

Since the area included by the median line of one turn of the secondary circuit exceeds slightly the actual cross-sectional area of the ring, a necessary correction was applied in reducing the observations to obtain the true flux density in the metal itself from the observed or apparent flux density as calculated from the galvanometer deflections.

If B' is this observed flux density, B the true flux density, and H the magnetising force, then from the dimensions given above we have

$$1.1129 B = 1.2097 B' - 0.0968 H.$$

In the first set of observations an ordinary magnetisation curve was taken, with gradually increasing magnetising forces (H), the flux density (B) being measured by reversing the force at each stage, and the corresponding permeability values (μ) being calculated for each value of B . The reduced figures of observation are given in Table I.

Table I.—Magnetisation Curve of Magnetic Alloy No. 1871, taken with Magnetic Forces varying from 1 to 50 C.G.S. Units.

Magnetising force in C.G.S. units.	Magnetic flux density in C.G.S. units.	Permeability.	Magnetising force in C.G.S. units.	Magnetic flux density in C.G.S. units.	Permeability.
H.	B.	μ .	H.	B.	μ .
1.10	18.6	16.9	20.80	496.5	23.84
2.19	32.45	14.8	21.90	530.0	24.2
3.28	56.90	17.35	23.0	564	24.5
4.28	77.7	18.15	24.1	599	24.82
5.48	100.05	18.25	25.2	636	25.22
6.57	122.4	18.65	26.28	659	25.05
7.66	144.4	18.86	27.4	703	25.64
8.46	167.5	19.8	28.5	738	25.88
9.86	192.3	19.52	29.6	780	26.35
10.95	218.0	19.9	30.7	811	26.4
12.04	238.5	19.8	31.8	845	26.56
13.14	270.0	20.54	32.85	877	26.7
14.23	294.8	20.7	33.95	922	27.15
15.32	323.0	21.06	35.05	955	27.24
16.41	351.6	21.4	37.25	1030	27.66
17.50	385.0	22.0	39.45	1096	27.78
18.60	419.0	22.5	41.6	1162	27.94
19.70	464.0	23.32	43.9	1236	28.15

A second magnetisation curve was subsequently taken, carrying up to force to a much higher limit, viz., 225 C.G.S. units, as far as it was safe to go without destroying the insulation of the primary coil. The figures obtained are given in Table II.

Table II.—Magnetisation Curve of Magnetic Alloy No. 1871, taken with Magnetic Forces varying from 4 to 225 C.G.S. Units.

Magnetising force in C.G.S. units.	Magnetic flux density in C.G.S. units.	Permeability.	Magnetising force in C.G.S. units.	Magnetic flux density in C.G.S. units.	Permeability.
H.	B.	μ .	H.	B.	μ .
4·36	75·64	17·36	83·21	2163·1	26·00
8·74	160·21	18·34	88·20	2221·0	25·18
13·12	260·56	19·88	91·80	2272·7	24·76
17·45	344·33	19·73	95·98	2303·5	24·00
21·83	467·9	21·43	100·33	2385·0	23·77
26·23	597·96	22·80	104·92	2412·9	22·99
30·77	749·21	24·35	109·49	2441·3	22·30
35·26	844·36	23·95	113·71	2497·1	21·96
39·47	1054·0	26·70	118·26	2552·7	21·59
43·86	1207·1	27·53	122·93	2571·6	20·92
48·15	1358·1	28·20	127·0	2606·1	20·52
52·66	1463·9	27·79	131·68	2662·7	20·22
57·04	1604·9	28·13	136·0	2690·3	19·78
61·36	1714·3	27·94	140·09	2716·7	19·39
65·58	1828·1	27·87	144·79	2773·0	19·15
69·83	1911·0	27·37	149·42	2799·0	18·73
74·28	1986·9	26·75	163·5	2802·0	17·14
78·57	2049·5	26·09	225·43	3013·1	13·36

The observations recorded in Table II are plotted into a curve in fig. 1, and show that the magnetisation curve for this magnetic alloy possesses all the well-known characteristics of a magnetisation curve of the ferromagnetic metals, iron, nickel, or cobalt. They show also that the permeability is a function of the flux density, and has a maximum value of nearly 28.

The next step was to take a number of cyclical magnetisation curves carrying the material through a magnetic cycle of operations, and employing various and increasing maximum values for the magnetic force.

In the Tables III to IX below, are recorded the reduced results showing the magnetic force and corresponding flux density in the case of the various cycles, the maximum value of the magnetic force in either positive or negative direction being given for each cycle.

The results of all these observations are embodied in a series of hysteresis loops or cyclical magnetisation curves, which are given in fig. 2. The range of maximum magnetic force for the various cycles extended from 10 to 70 C.G.S. units.

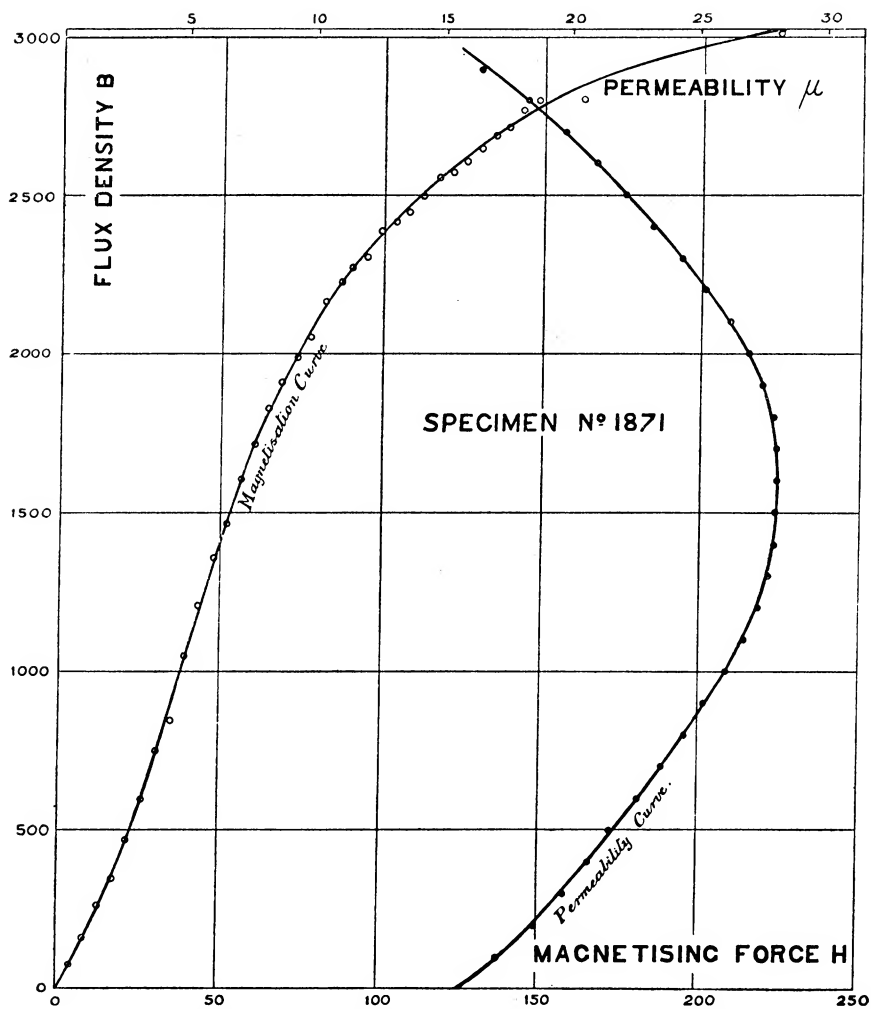


FIG. 1.—Magnetisation and Permeability Curves of Alloy No. 1871.

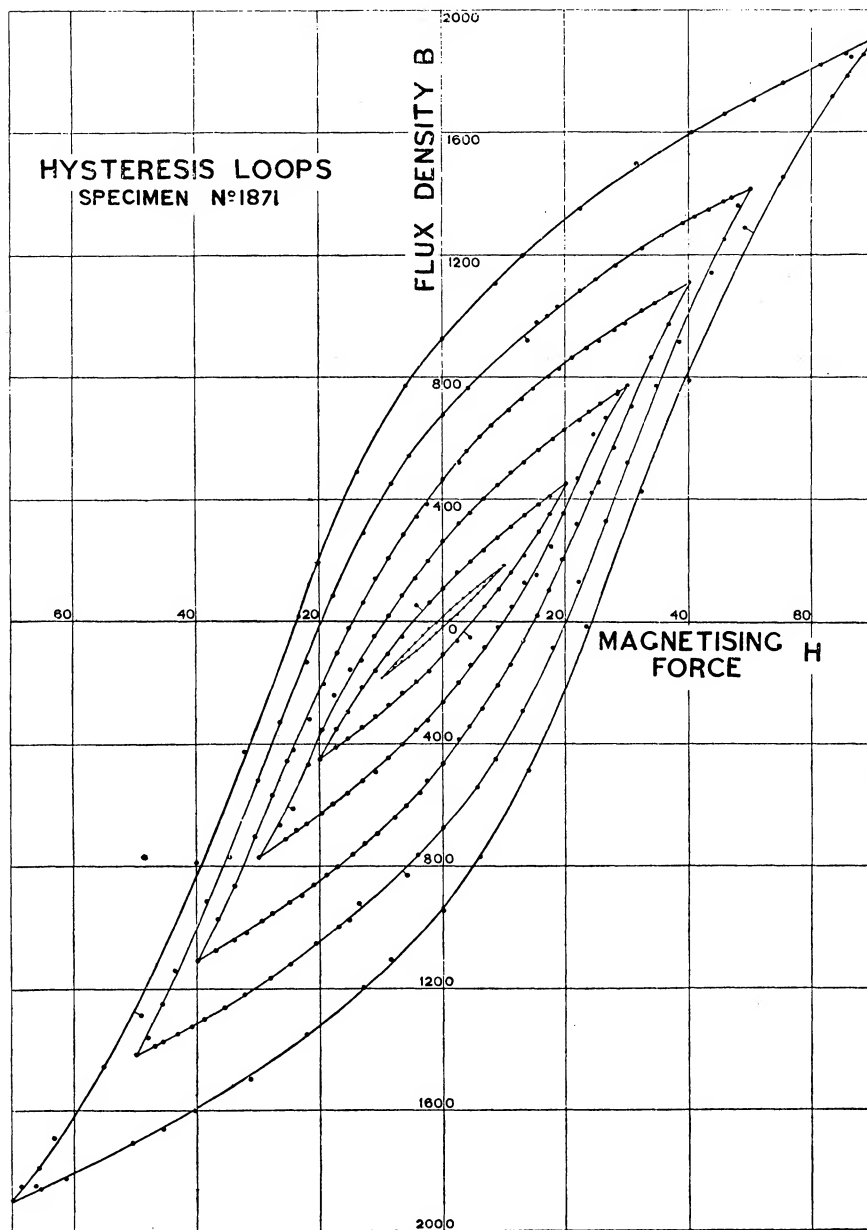


FIG. 2.—Hysteresis Loops of Alloy No. 1871.

Table III.—Cyclical Magnetisation Curve for Magnetic Alloy No. 1871.
Maximum Value of Magnetising Force = 10 C.G.S. Units.

Force positive and decreasing.		Force negative and increasing.	
Magnetising force in C.G.S. units.	Magnetic flux density in C.G.S. units.	Magnetising force in C.G.S. units.	Magnetic flux density in C.G.S. units.
+ H.	B.	− H.	B.
9·06	170·4	1·095	5·69
7·92	149·9	2·256	22·95
6·68	131·2	3·329	46·7
5·59	115·7	4·46	69·03
4·43	96·32	5·598	92·08
3·255	77·22	6·627	115·15
2·186	57·73	7·726	138·2
1·09	37·87	9·023	167·0
0·0	16·32	10·0	184·3

The numbers under the column headed + H are the gradually decreasing but positive values of H, to which the force is reduced each time from the maximum value +10.

The numbers under the heading − H are the negative values of H, to which the force is suddenly changed from +10.

The corresponding values of B delineate one-half of the hysteresis loop.

Table IV.—Maximum Value of Magnetising Force = 20 C.G.S. Units.

+ H.	B.	− H.	B.
17·42	413·4	2·31	61·85
15·496	385·0	4·44	6·00
13·17	347·6	6·69	49·85
10·96	310·6	8·90	105·7
8·796	275·2	10·95	161·5
6·633	233·8	13·16	217·4
4·44	195·5	15·48	295·6
2·295	162·2	17·45	351·6
0·0	106·5	20·0	452·1

Table V.—Maximum Value of Magnetising Force = 30 C.G.S. Units.

+ H.	B.	+ H.	B.	− H.	B.	− H.	B.
28·48	753·6	13·21	521·45	2·46	199·27	17·62	242·76
25·57	713·35	10·97	492·36	4·47	142·66	19·64	355·1
23·76	684·2	8·87	447·16	6·68	86·58	21·88	468·8
22·19	660·3	6·61	401·92	8·86	19·03	24·41	551·7
19·74	627·9	4·39	356·4	11·17	48·9	26·55	666·4
17·86	598·3	2·46	322·15	13·15	128·0	28·43	745·75
15·53	561·08	0·0	263·38	15·24	157·0	30·00	773·8

Table VI.—Maximum Magnetising Force = 40 C.G.S. Units.

+H.	B.	+H.	B.	—H.	B.	—H.	B.
37·01	1077·0	17·23	801·9	2·64	385·8	19·45	203·88
34·21	1042·7	14·69	762·7	4·29	343·1	21·65	319·98
32·32	1019·0	12·82	728·0	6·36	286·0	24·25	423·68
29·51	979·1	10·67	694·2	8·89	208·6	25·33	456·8
27·77	954·6	7·93	643·2	10·98	141·8	27·72	568·8
25·39	920·1	6·01	603·6	13·02	72·5	30·58	705·5
23·39	897·8	3·78	558·4	15·28	24·82	33·94	867·4
21·05	864·3	2·64	521·2	15·30	21·47	36·68	975·1
18·89	829·8	0	464·9	17·2	102·83	40·00	1112·0

Table VII.—Maximum Magnetising Force = 50 C.G.S. Units.

+H.	B.	+H.	B.	—H.	B.	—H.	B.
46·87	1388·8	24·91	1122·0	5·50	542·4	34·69	772·8
45·56	1376·1	22·33	1085·0	8·47	452·9	38·36	918·0
43·16	1350·8	20·73	1053·9	12·92	292·86	43·67	1144·0
40·88	1327·1	18·67	1031·8	17·77	87·59	45·66	1253·9
39·01	1303·8	17·04	999·4	22·15	132·1	48·0	1364·0
35·58	1264·6	15·26	975·5	26·52	331·1	50·0	1419·3
33·89	1245·7	13·69	922·1	30·03	522·0		
32·35	1221·9	5·91	830·9				
30·10	1189·3	4·25	763·8				
28·13	1167·3	0	674·8				

Table VIII.—Maximum Magnetising Force = 60 C.G.S. Units.

+H.	B.	+H.	B.	—H.	B.	—H.	B.
55·05	1561·5	27·56	1236·2	6·56	351·74	36·17	807·0
54·56	1559·1	22·25	1158·5	10·62	406·01	40·88	1003·0
50·05	1509·6	19·73	1122·0	15·16	240·29	45·53	1273·0
45·37	1460·4	14·2	1025·3	19·52	62·0	50·15	1449·8
40·58	1406·8	9·97	956·4	23·61	132·9	53·16	1557·3
36·10	1349·0	5·73	868·6	28·29	381·6	54·93	1613·1
32·35	1299·6	0	745·8	31·68	560·0	60·0	1612·9

Table IX.—Maximum Magnetising Force = 70 C.G.S. Units.

+H.	B.	+H.	B.	—H.	B.	—H.	B.
65·17	1859·9	31·60	1495·5	5·87	769·1	55·14	1457·8
61·42	1823·6	22·40	1350·6	13·88	487·2	63·33	1693·7
55·29	1763·2	13·51	1206·0	23·52	18·8	65·65	1797·5
50·52	1706·0	8·64	1115·8	32·14	429·4	66·35	1855·3
45·94	1664·0	0	925·6	40·12	790·2	68·65	1855·1
40·75	1604·1			49·14	1292·0	70·0	1904·9

The figures in the above tables having been set out in the form of hysteresis loops or cyclical magnetisation curves, the areas of these curves were taken in square centimetres, and by division by 4π , the energy loss in ergs per cubic centimetre per cycle of magnetisation was obtained. The final results are set out in Table X.

Table X.—Cyclical Magnetisation Curves and Hysteresis Energy Losses per Cycle of Magnetic Alloy No. 1871.

Maximum value of the magnetising force in C.G.S. units in each cycle.	Maximum value of the flux density in each cycle.	Energy loss in ergs per cub. cm. per cycle = area/ 4π .
$H_{\max}$.	$B_{\max}$.	E.
10	184.3	35.02
20	452.1	464.8
30	773.8	1589.2
40	1112.0	3600.4
50	1419.3	6336.0
60	1613.0	7258.0
70	1859.9	10880.0

From the figures in Table X a curve can be set out (see fig. 3) which delineates the relation between E and $B_{\max}$, or the energy expenditure required to carry the magnetic alloy through one complete magnetic cycle of operations and the maximum value of the flux density during that cycle. This curve is shown in fig. 3 (on the left hand) as a curve concave upwards. If, instead of plotting in terms of E and $B_{\max}$ as taken from Table X, we plot the logarithms of these quantities, we obtain a nearly straight line, as shown on the right-hand side of diagram 3.

The values in Table X show that the energy loss per cycle may be represented as an exponential function of the maximum flux density by an expression of the form

$$E = \eta B_{\max}^n,$$

where n is some exponent and η some constant.

We find the numerical values to be best represented by the expression

$$E = 0.0005495 B_{\max}^{2.238}.$$

The exponent n in the case of iron, nickel, and cobalt is a number not far from 1.6. In the case of this alloy the hysteretic exponent between $H_{\max} = 10$ and $H_{\max} = 70$ has a much higher value, viz., 2.238.

From the above observations we are then able to draw the following conclusions :—

(i) The alloy No. 1871, composed of copper, aluminium, and manganese, in the proportion mentioned above, exhibits magnetic properties which are identical with those of a feebly ferro-magnetic material.

(ii) The magnetisation (or B, H) curve is of the same general form as that of a ferro-magnetic metal such as cast iron, and indicates that with a

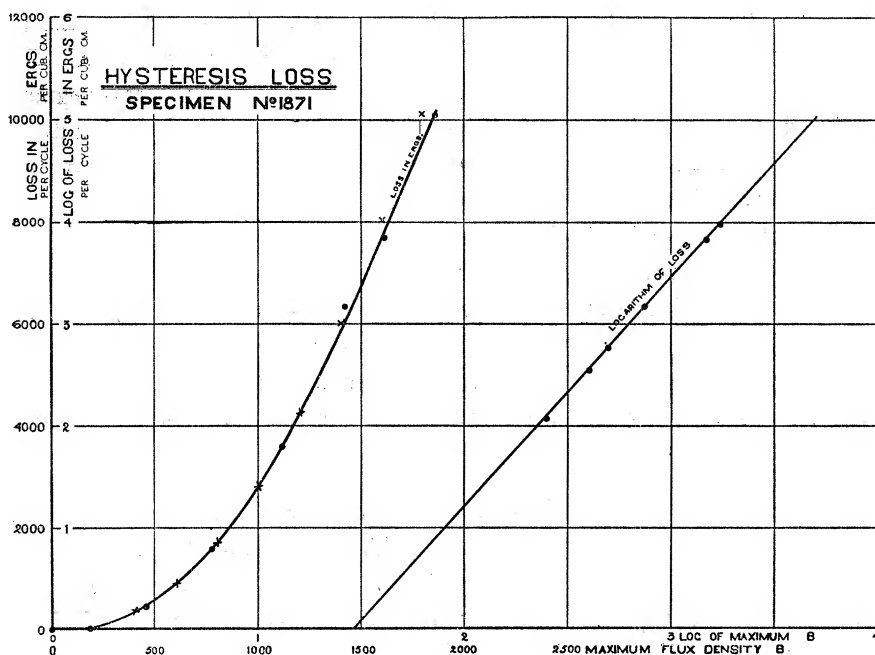


FIG. 3.

sufficient force, a state of magnetic saturation would most probably be attained.

(iii) The alloy exhibits the phenomenon of magnetic hysteresis. It requires work to reverse the magnetisation of the material and to carry it through a magnetic cycle.

(iv) The material has a maximum permeability of 28 to 30, which is not greatly inferior to that of the values reached for cobalt or a low grade of cast iron for small magnetic forces, and occupies a position intermediate between the permeability of the ferro-magnetic and the merely para-magnetic bodies, such as liquid oxygen and ferric chloride.

(v) The material exhibits, therefore, the phenomenon of magnetic

retentivity and coercivity. It is not merely magnetic, but can be permanently magnetised.

We are led by these results to conclude that the magnetic properties of this alloy must be based on a certain similarity of molecular structure with the familiar ferro-magnetic metals.

The hypothesis which best fits the facts of ferro-magnetism is that materials, such as iron, nickel, and cobalt, are composed of molecular groups which are permanently magnetic, and that the process of producing or changing the evident magnetisation of a mass of these metals consists in arranging or disturbing the positions of these molecular magnets. Since then, we have in this alloy an instance of fairly strong ferro-magnetism produced by an admixture of metals possessing in themselves separately no such property, it follows that ferro-magnetism *per se* is not a property of the chemical atom, but of certain molecular groupings.

The importance of this fact cannot be easily overstated. It shows us that in spite of the fact that ferro-magnetism has been hitherto regarded as the peculiar characteristic of certain chemical elements—iron, nickel, and cobalt—it may, in fact, depend essentially on molecular grouping composed of a comparatively large number of molecules, and, hence, it may be possible to construct alloys which are as magnetic or even more magnetic than iron itself.

[*Note added June 2.*—We have furthermore conducted experiments on the magnetic qualities of the alloy No. 1888/7, and we find them generally to be similar to those of the alloy No. 1871. The alloy No. 1888/7 has less manganese (about 5 per cent.) and more copper (about 8 per cent.) in it than the alloy No. 1871. In addition, alloy No. 1888/7 contains 4 per cent. of lead. The magnetisation curve of the alloy No. 1888/7 was taken with gradually increasing magnetising forces up to $H = 220$. The magnetisation curve is rather flatter than that of ring No. 1871, and the maximum permeability reaches a value of only 14 for sample No. 1888/7, instead of nearly 28. A series of hysteresis loops was taken between the same limits of magnetising force as in the case of ring No. 1871, and from their areas a curve set out showing the hysteresis loss in ergs per cubic centimetre per cycle (E) in terms of the maximum value of the flux density during the cycle ($B_{\max}$). We found that the relation of these two quantities could be expressed by an exponential function, viz. :—

$$E = 0.000776 B_{\max}^{2.238}.$$

Hence it appears that for both alloys No. 1871 and No. 1888/7 the hysteretic exponents are not very different, being respectively 2.238 and

2.288, whereas the hysteretic constants are very different, being respectively 0.0005495 and 0.000776.

It is clear, therefore, that both these alloys, although magnetic, have far greater hysteresis than pure iron, nickel, or cobalt, for corresponding cycles of magnetisation.

We hope to find opportunity of carrying out similar experiments at various temperatures, as the determination of the critical temperature at which these alloys will lose their magnetic susceptibility is evidently a very interesting matter.]

In conclusion, we desire to record our thanks to the actual observers who have taken the many thousands of observations necessary to obtain the figures here given. This observational work was done by Messrs. Westerdale, Bullman, Ramsay, Tarlton, and Nichols, students working in the Pender Electrical Laboratory of University College, London. The work was carefully superintended by Mr. W. C. Clinton, B.Sc., the demonstrator in the Pender Laboratory, to whom also thanks are due for the care with which it has been carried out.
